

OPTICAL FIBER PROBE FOR POSITION MEASUREMENT

This invention relates to improved emitters of electromagnetic rays. It more particularly refers to such emitters that are more nearly perfect point sources of electromagnetic rays than have been available in the prior art. It also refers to a novel method of determining the location of points in three dimensional space using such nearly perfect point sources of electromagnetic radiation.

BACKGROUND OF THE INVENTION

The electromagnetic rays to which this invention refers are often, but not necessarily, in the visible spectrum. The substantially point source emitters of this invention are suited to be disposed on a supporting object, of known size and shape, whose position and orientation are being determined in a three dimensional coordinate system from a determination of the locations of these emitters in the same coordinate system. They may also be disposed on one or more stationary and/or moving objects, of known size and shape, whose position(s) and orientation(s) are being tracked as it moves in space within a three dimensional coordinate system. In this use as a position and orientation determinant, the emitter is seen by a plurality of electromagnetic ray receptors, which are generally referred to herein as cameras.

The straight ray lines between a plurality of either the emitter(s), or the camera(s), or both, can be compared to straight reference lines to thus form a plurality of angles from which geometric information is obtained. This geometric information can, in turn, be used to determine the precise location(s) of the emitter(s) in space, and from these emitter locations, if the shape and size of the object are known, the position and orientation of the object on which the emitter(s) reside can be determined geometrically. Since the location of the emitter(s) can be tracked substantially continuously, or at least very frequently, movements of the object on which they are disposed can be tracked. The more frequently the locations of the emitters are determined, the more precise is the movement tracking ability of the system. Further, the smaller and less variant the emitter source of the electromagnetic rays, the more accurately can its location be determined. That is, the closer the emitter resembles a point source, which is in the same apparent location [is] in space regardless of the angle from which it is viewed by the camera(s), the more accurate can its location be determined in a three dimensional coordinate system. It follows that the more accurate is the determination of the locations of the point sources, the more accurate is the determination of the position(s) and orientation(s) of the object(s) supporting the emitters.

Systems for tracking or determining the position and orientation of objects in space by means of measuring the angles intersected by beams of emitted electromagnetic radiation, either between two such beams, or between one such beam and a reference beam or line, are known. Reference is made to U.S. patent application Ser. No. 08/317, 805, now U.S. Pat. No. 5,622,170, the entirety of which is incorporated herein by reference, which discloses a system for determining the spatial position and orientation of the object, by means of determining the location of emitters of electromagnetic rays which are disposed on its surface, using electro-optical sensors. In order to improve their accuracy, there is a desire for these emitters to more closely approximate or resemble a point source of emitted radiation.

As referred to herein, a point source emitter(s) are tiny, but finite dimensioned, radiating (sometimes luminous) bod-

A number of such electromagnetic sensors have been described in published literature and have been used in spaced apart pairs or triples to determine the location of an electromagnetic radiation emitter in 3-dimensional space. A commercially available example is the FlashPoint 5000 system, manufactured by Image Guided Technologies of Boulder, Colo. That and other examples of systems using linear (one-dimensional) detectors are described in the following references to the state of the prior art:

FlashPoint 5000 Users Manual; Image Guided Technologies, Inc., Boulder, Colo., 1996.

H. Fuchs, J. Duran, B. Johnson, and Zvi. M. Kedem; "Acquisition and Modeling of Human Body Form Data", Proc. SPIE, v. 166, 1978, p 94-102.

Jean-Claude Reymond, Jean-Luc Hidalgo; A System for monitoring the movements of one or more point sources of luminous radiation, U.S. Pat. No. 4,209,254, Jun. 24, 1980.

Y. Yamashita, N. Suzuki, M. Oshima; "Three-Dimensional Stereometric Measurement System Using Optical Scanners, Cylindrical Lenses, and Line Sensors", Proc. SPIE, v. 361, 1983, p. 67-73.

F. Mesqui, F. Kaeser, and P. Fischer; "real-time, non-invasive recording and 3-d display of the functional movements of an arbitrary mandible point", SPIE Biostereometrics 602 (1985) p 77-84.

Sharon S. Welch, Kevin J. Shelton, and James I. Clemmons; A Optical position measurement for a large gap magnetic suspension system, Proc. of the 37th International Instrumentation Symposium, San Diego, May 5-9, 1991, p. 163-182.

Waldean A. Schulz; A Method and apparatus for three-dimensional non-contact shape sensing, U.S. Pat. No. 5,198,877, issued Mar. 30, 1993.

Farhad Daghighian; A Optical position sensing with duolateral photoeffect diodes, Sensors, 1994 November, p. 31-39. Examples of systems using two-dimensional detectors are found in the following references, which reflect the state of the prior art:

U.S. Pat. No. 4,896,673 by Rose et al.

U.S. Pat. No. 4,836,788 by Baumrind et al.

Provided there is a way to distinguish between the emissions of multiple electromagnetic energy emitters (for example LED's) that are mounted on a substantially rigid object, of known size and shape, the position and orientation of the object can be geometrically derived from the determined locations of the several emitters. To at least a limited extent, even the shape of an unknown object can be determined if a sufficient number of LED emitters are attached to each of its surfaces (see for example the '788 patent cited above). The more complicated the shape of the object, the more emitters are required to define its shape. Each emitter may be distinguished by a unique emission wavelength, by its relative location in some unambiguous geometrical pattern of emitters, or by its ordinal position in a serial emitting sequence. It is possible that other means of distinguishing between several emitters are known or will be discovered in time.

To date, in the field of tracking objects moving in space, the electromagnetic energy emitters, whose locations are to be determined, have usually been visible or infrared, light emitting diodes (LED's). Other wavelengths of electromagnetic radiation, in addition to the visible spectrum, are also well suited to use in this environment. The specific wavelength of the emitted radiation is not a limitation on the practice or scope of this invention.

Unfortunately, a conventional LED, which radiates in any given, predetermined wavelength, has several drawbacks to its use as a point source electromagnetic energy emitter. At the present time, electromagnetic energy emitting semiconductor chips (LED's) are conventionally disposed in a protective, substantially transparent epoxy envelope. Protecting the semiconductor chip, and its electrical connections, are extremely important. However, [One] one drawback of this necessary epoxy envelope is that it refracts the light rays that are being emitted by the chip, which shifts the

A second drawback is that the LED semiconductor chip, which may be as large as 1 millimeter square and is usually mounted on a partially reflecting surface, does not radiate uniformly, even without the protective epoxy coating. This can cause an apparent shift in the location of the centroid of illumination as the cameras' view of the chip is rotated about the geometrical centroid of the chip. Furthermore, the chip typically has attached to its top, an electrical contact wire or metallic strip, which partially eclipses (or reflects) the light from part of the chip and introduces asymmetry into the radiation pattern. These effects limit the accuracy and repeatability of precisely locating the chip optically, particularly if the goal is to determine a coordinate that has a smaller margin of error than the size of the chip.

A third drawback occurs when the LED's are sequentially flashed as a way to unambiguously identify individual LED's. The flashing may generate electromagnetic interference unless the waveform of the current flow through each LED is carefully controlled. Even in that case, the wires to the LED's tend to act as antennae, transmitting out other electronic noise from the control box, which in practice generates high frequency control signals which are often picked up by the electromagnetic sensor assembly.

A fifth drawback exists when the LED's are used within a medical nuclear magnetic resonance imager (MRI). The metal electrical leads, the currents flowing through them, and the metallic case or heat sink (if used) deforms the MRI's magnetic fields and thereby can warp the image of the patient.

LED is replaced.

55 An LED as a generator of light is not a problem. In fact, an LED can be flashed much faster than an incandescent source. An LED is nearly monochromatic, allowing the position measurement sensors to use a narrow-band filter to cut out most interfering background illumination. LED's are

60 inexpensive and have a long life. A laser diode, which is a very special kind of LED, is especially good for coupling light into an optical fiber. These characteristics, and the present lack of a suitable alternative light source, suggest that LED's, or the special case laser diodes, can be expected

65 to continue to play a role in the determination of the position and orientation of objects in space. Therefore, solutions to the above problems must be determined.

Optical fibers, or bundles of optical fibers, are a good way to transport light from a source to a destination. However, they possess a major drawback to their use as light source, in the types of systems that are used for determining the locations of electromagnetic emitters, such as those described above. The drawback is that when the optical fiber end is considered to be the light source, the cone of light emitted from the end of a fiber (or fiber bundle) has an inconveniently narrow apex, or conical, angle. For the purposes of tracking an object which may have an arbitrary orientation, the light emitters on the object should ideally radiate uniformly over at least a substantial portion of a [full] hemisphere, preferably at least the entire full hemisphere, and ideally, approaching a substantial whole of a sphere.

OBJECTS AND SUMMARY OF THE INVENTION

Therefore, it is an important object of this invention to provide a new practical and effective way to produce substantially point source emissions of electromagnetic ray energy from locations on objects to be tracked in three dimensional space by an electro-optical location determination system.

Another objective of the present invention is to improve how relatively tiny point source emitters of electromagnetic ray energy are implemented, particularly where the locations of the emitters are to be tracked in three-dimensional space using an electro-optical position determining system.

A further object of this invention is to provide means for ameliorating each of the drawbacks listed above.

Other and additional objects of this invention will become apparent from a consideration of this entire specification including the drawing hereof.

This invention will be described through the example of the use of multiple emitters of light attached to a probe, which is to be used for pointing purposes, in relation to a given three dimensional space (a 3-d volume). It is to be understood that this descriptive reference is only for illustration purposes. The object having electromagnetic ray emitters disposed thereon could be any object, or a plurality of objects, whose position(s) and orientations are to be tracked within a 3-d volume with respect to a coordinate system. Examples of such objects are a robot arm, an observer's head in a virtual reality display system, a computer, a mouse, a surgical instrument, a patient on which the instrument is being used, or the like, or even combinations of such objects.

Each emitter of the present invention is suitably illustrated by a laser diode or LED, but other light sources can be used. Suitably, a lens couples the electromagnetic rays emerging from the light source into one end of an optical fiber or fiber bundle, and an optical element (the substantial point source electromagnetic emitter of this invention) at the other end of the fiber or fiber bundle suitably disperses the light into a very wide and substantially uniform emission pattern. Specifically, it is this dispersing optical element on the end of an optical fiber, and its use in the context of 3-d object tracking, to which this invention refers.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying figures, which form a part of the specification, illustrate a preferred embodiment of the present invention and some variations thereof. Together with the textual description, these figures serve to explain the principles of the invention. A specific reference number in

the figures consistently refers to the same component of the invention throughout all the figures and in the textual description.

5 FIG. 1 is a schematic view of an otherwise conventional system that can adopt the use of the instant invention;

FIG. 2 is a perspective view of a probe, light source and optical fiber light guides;

10 FIG. 3a is a plan view of one aspect of a point source emitter according to this invention;

FIG. 3b is a perspective view of one embodiment of this invention;

15 FIGS. 4, 5, 6, 7 and 8 are perspective views of other embodiments of this invention.

The components of the conventional digitizing and measurement system that are used in one aspect of this invention as shown in FIG. 1 include: an object 12 to be tracked in a 20 3-d volume relative to a reference coordinate system 10. The particular object to be digitized in a 3-d volume relative to a reference coordination system. One example of this object that is depicted in the figures is a stylus or probe with a tip 25 14 which may be used for pointing purposes. In FIG. 1, emitters 18 are shown in their conventional configuration. In FIG. 2, two laser diodes 20 are shown as the generators of light (the light sources). This invention contemplates any number of light sources, but only two light sources are 30 shown in order to keep the figures uncomplicated. Lenses 22 couple the light from the corresponding sources 20 into one end of the optical fiber (or bundles of fibers) 24 which serve to transmit the light to the emitters 26. Each generic optical emitter element 26, disposed at the other end of the fiber, or 35 fiber bundle, disperses the light into a very wide radiation pattern 28. Optical elements 26a (specific and illustrative forms of the generic optical element 26 that have been shown in FIG. 2) shown in FIGS. 3a and 3b are, respectively, a diffusing sphere and a diffusing plate. 40 Another optical element 26b, shown in FIG. 4, is a tapered light pipe or image guide of special configuration sufficient to emit light dispersed in a substantially hemispherical pattern. A further optical element 26c, shown in FIG. 5, is a special concave lens.

45 Exemplary rays of light 28 are radiated outward by each of the optical elements, a few of which are [Asect=] seen by the sensor assembly 30 (see FIG. 1). A support electronics system 32 powers and controls the sensor assembly 30 and 50 the light sources. The support electronics 32 also processes the input from the sensor assembly 30. An otherwise conventional electronic computer 38 receives the input of the data from the support electronics 32. From these data, the computer 38 calculates the XYZ coordinates of the location 55 of each optical element, 18 or 26, etc, which appears as a substantial point source emitter of light. From the thus determined coordinates of each emitter, and the known geometry of the probe, the computer 32 also computes the position and orientation of the probe and therefore determines the location of the probe tip. It also determines a unit 60 3-d vector describing the longitudinal direction of the probe (which is one aspect of the orientation of the probe). If more than two non-collinear electromagnetic energy ray emitters are disposed on the probe, a transverse 3-d vector can also 65 be computed to describe its rotational orientation (or its A roll angles). The various figures are numbered throughout as follows:

10	reference 3-d coordinate system (rectangular)	
12	object to be tracked (such as a probe, as shown)	
14	tip of probe	
18	conventional optical emitters	5
20a, ...	laser diodes	
22a, ...	coupling lenses	
24a, ...	optical fibers or bundles of optical fibers	
26	optical element (general)	
26a	optical element: diffusing sphere or plate	
26b	optical element: tapered light pipe	10
26c	optical element: concave lens	
30	sensor assembly of position measurement system	
32	emitter and sensor support electronics	

The invention will be described below with reference to the figures and the numbered individual components therein. In the description below, the specific construction, the number, arrangement of the components are all intended for simplicity of explanation. Other construction, number and arrangements of the same functional components constitute, encompassed alternative embodiments of the instant described method and apparatus.

DETAILED DESCRIPTION OF THE INVENTION

In reference to FIGS. 1 and 2, note should be taken that the present invention can use substantially the same supporting equipment as was used in prior art systems. This equipment consists of an electro-optical sensor assembly 30 (e.g. the camera array), an electronic control box 32, and an electronic computer 38. The only difference between the support components used in this invention and those used in prior art systems is that in the prior art the control box 32 usually generated electrical pulses to fire the LED's 18, that are shown in FIG. 1 to have been previously disposed on the probe 12 (or another such object to be tracked). In the present invention the same electric pulses fire the laser diodes 20 of FIG. 2, which are, at least in a preferred mode, preferably disposed remote from the object 12 being tracked. The laser diodes 20 are preferably located in the control box 32 itself in order to limit their emission of spurious electromagnetic radiation. Alternatively, the laser diodes 20 can be housed in a separate box or even in the handle of the probe 12 itself. Although there may be some disadvantages to situating the light sources within the probe body because stray radiation might interfere with other surrounding operations as aforesaid, there is a distinct economic advantage to situating the ultimate light sources within the probe handle. The advantage of this option is that a probe of the prior art could be upgraded to a probe of the present invention without requiring any change to the supporting equipment. This may be an advantage in connection with some existing systems, particularly where cost of upgrading is a factor. In either case, the operation of the system of this aspect of this invention is substantially the same regardless of where the ultimate light source is located. In a preferred embodiment, the ultimate light source is remote from the emitter, but it does not absolutely have to be so. In this regard, the instant invention enables owners of prior systems to upgrade them to the system of this invention without substantial remodeling costs.

Just as in the prior art, the laser diodes 20 can be sequentially activated (flashed) and their light transmitted to their respective emitters according to this invention, and thereby these emitters will flash sequentially and they can then be located individually. Alternatively, each of the laser diodes 20 can be controlled to operate continuously, rather

than sequentially. In this aspect of this invention, each laser diode will be set to generate different wavelengths of light rays 28, respectively, in order to uniquely identify each of the point source emitters of light 26. Alternatively still, the optical elements 26 can be disposed in such a geometric pattern that the optical elements are unambiguously identified by their location (such as at the vertices of an irregular polygon or polyhedron).

In any case, the sensor assembly will sense these emissions and will return raw data of the location of each emitter through the control box 32 to computer 38 which is running a software program to compute XYZ coordinates relative to the coordinate system 10 from the raw sensor data. In practice the raw data from the sensor assembly 30 could be analog data which the control box 32 could convert to digital data. The final 3-d coordinate computation would be done by the computer 38 which could be a standard personal computer or workstation. Of course, this invention is not limited to the specific computer that is chosen for implementation of the mensuration aspects hereof.

The sensor assembly 30, the supporting control electronics 32, and the calculations in the computer 38 are not substantially different from the prior art. Therefore, no further details about them will be discussed. They could be off-the-shelf, commercially available systems, and therefore they are disclosed herein only by reference to the above mentioned technical papers and patents.

Four alternative embodiments of the optical emitter elements will be presented. Each operates slightly differently, but the effect is the same: light from a suitable source, such as a laser diode, is transmitted through the optical fiber to a suitable emitter, and then radiates in a much wider cone than it would have from the fiber alone without the intervention of the optical emitter elements. Furthermore, the sensor sees the effective point from which the light appears to come is tiny, and its centroid does not vary with the orientation angle of the optical emitter element with respect to the sensor assembly. If the light sources, for example laser diodes, or LED's, are housed in the control box 32 and it is well shielded against spurious electromagnetic radiation, no, or at least only a very small amount of spurious electromagnetic radiation will escape, and only the intended light will be transmitted inside the optical fiber(s). The probe can be designed to be completely neutral electrically and magnetically. Therefore, the probe can be designed to be wholly non-metallic. Lastly, in the configuration of this invention, the optical fibers and optical emitter elements do not burn out and can be made to be as small as, or even smaller than, LED light sources. In addition, these light emitter elements used in this invention operate directly and without sockets. On the other hand, the hand, the laser diodes, which are subject to burning out and need to be replaced, can be situated where they can be readily replaced as necessary (such as inside the control box 32. In a less preferred embodiment of this invention, they can be disposed in the handle of the probe itself). The location of the actual light which is the origin of the radiation being emitted by the practice of this invention can be made by the system designer without affecting the practice of this invention. It is to be understood that in a preferred embodiment of this invention, the electrically driven light source is spatially removed from the probe itself.

The optical fibers 24 themselves can be any diameter, such as for example 400 microns. That is, they might be finer and lighter than the wire pairs that were previously used to power the light sources. Yet, they can be large enough to simplify the problem of efficiently coupling in the light from

the laser diodes 20 to the optical fiber or fiber bundle. Because the distances traversed by these optical fibers 24 are so short, and the information they carry is so simple, the fibers 24 can sustain higher internal losses than long-distance communication fibers. For example, they could be inexpensive plastic, such as polymethyl methacrylate, instead of the more expensive and lower loss silica.

A first embodiment of the critical optical element 26 of this invention is shown in figure 3a. In this case the light is uniformly and widely dispersed by means of a tiny diffusing sphere 26a which is optically coupled to the end of the optical fiber. This is the preferred embodiment of this invention because it can very uniformly disperse light omnidirectionally (in substantially all directions). Such diffusing spheres are, for example, manufactured by Rare Earth Medical, Inc. (West Yarmouth, Mass.) for use in laser oblation surgery (but not for geometrical localization purposes). Such diffusing spheres are transparent epoxy balls with minute particles of reflective powder suspended inside. The combination of light reflecting off the particles and refracting around them scatters the light in all directions quite uniformly. The only drawback to this embodiment occurs when a sphere is partially eclipsed by the handle of the probe (or other such object). In this [Asunset=] sunset situation, the centroid of the visible portion of the sphere will shift away from the geometrical center of the sphere.

The sunset situation can be eliminated by using a planar diffuser, such as the one shown in the configuration depicted in FIG. 3b rather than a sphere as shown in FIG. 3a, and insuring that its plane is tangent to the curve of the probe handle. If the planar diffuser 26a is viewed from a normal direction (that is, head-on), the narrow cone of light emitted from the optical fiber 24 creates a bright luminous circular disk on the diffuser 26a. As this disk is viewed from larger angles from the normal, the disk appears as an ellipse, but the centroid remains in the middle. The light intensity distribution from this configuration is Lambertian; that is, most of the light is radiated in a direction that is normal to the plate, and less is dispersed at larger angles with respect to the normal direction. Mathematically, the intensity is proportional to the cosine of the viewing angle, as measured with respect to the normal direction. For example, the intensity falls to zero as the viewing angle approaches 90 degrees from normal.

A second embodiment of the optical element 26 of this invention is shown in FIG. 4. In this case the light is widely dispersed by means of a special optical fiber bundle 26b called an image guide or a light pipe. It is preferably tapered to concentrate the light into a smaller spot and it has a high numerical index to widen the emission angle of the cone of radiation. Such fiber bundles are available from Collimated Holes, Inc., (Campbell, Calif.).

In any embodiment of this invention, the optical fiber bundles may be randomly organized and need not preserve image geometry because they are only being used as light transmitters. If the fibers of the light pipe have a high index of refraction (a numerical aperture value near 1.0), the light will be radiated throughout substantially a full hemispherical pattern. Even though the intensity of light diminishes with the cosine of the angle of the direction of radiation (measured relative to the optical axis of the fibers, far more light is radiated in directions which are substantially parallel to the axis of the fibers and much less at steeper angles) Even so, there is sufficient radiated light to be "seen" by the camera array. This is shown in FIG. 4 as a higher concentration of rays 28 in the forward direction (that is substantially parallel to the axis of the fiber than in a direction normal to the fiber axis.

Note that in the embodiment shown in this figure, the whole optical fiber 24 and the light pipe 26b could be one and the same element if they were properly designed. That is, the optical fiber 24 may simply be a long flexible light guide with a large (wide) numerical aperture at its end. Conventional optical fibers have not been found to produce satisfactory large conical emission angles, without first being modified. [Therefore, this aspect of this large conical emission angles, without first being modified.] Therefore, this aspect of this invention has been developed specifically to overcome this deficiency.

Note should be taken that, in the embodiment shown in this FIG. 4, the optical fiber 24 and the coupling lens 22 could be omitted and the light source 20 could be placed directly within the probe directly behind the optical element 26. While this does not avoid creating electronic and magnetic interference (because an electrical cable to the probe would then be required), it still overcomes some of the disadvantages listed in the section of this specification captioned Background of the Invention. However, even though this alternative is considered to be within the scope of this invention, this is not a preferred embodiment of this invention. In this regard, note should be taken of the configuration shown in FIG. 8.

A third embodiment of the optical element 26 is shown in FIGS. 5 and 6. FIG. 5 is an oblique view and FIG. 6 is a cross-section view showing in better detail the action of the lens of this embodiment on the rays of light. In this case, the light is widely dispersed over a substantially complete hemisphere by means of a tiny concave lens 26c. The lens is designed to produce a tiny virtual image of the end of the optical fiber which is visible even at very extreme angles. That is, the light is not only radiated in the "forward and near forward directions", that is substantially parallel to the axis of the transmitting optical fiber, but it is also radiated in directions which approach being parallel to the planar surface of the lens, that is substantially transverse to the axis of the optical fiber or fiber bundle. Note that if the end(s) of the transmitting optical fiber is rounded, or a convex lens or optically transparent ball is placed over the end of the fiber, the emitted light will diverge somewhat, but the angle of the cone of emitted light does not exceed approximately 90 degrees, which is still too narrow to be practical without further modification by the further use of a lens of this embodiment. For this reason, it is most preferred to use a concave lens. In this regard, a rounded end of the optical fiber coupled with a concave lens will be quite effective.

A fourth embodiment of the optical element 26 of this invention is shown in FIG. 7. In this embodiment, the light coming out of the transmitting optical fibers is reflected off of a tiny curved (hyperbolic) mirror 26d. This is the reflective optical counterpart to the refractive element 26c shown in other figures. The advantage of this arrangement is that the light can be spread over a wide annular ring of angles. The drawback to this arrangement is that the optical fiber or the mirror itself eclipses the reflected light at angles near the optical axis (both forward and backward).

The above description has presented four specific embodiments of the operationally substantially at least hemispherical optical radiating elements of this invention. Each of these embodiments is illustrative of the instant invented means of making optical fibers practical for use in an electro-optical system for tracking an object, such as a probe or pointer, with two or more point source light emitters. The optical elements facilitate increased accuracy, nearly perfect electrical and magnetic isolation, and no generation of spurious radiation. The passive optical fibers on the object itself